

MODELING OF COMBINED HEAT AND POWER PLANT BASED ON A MULTI-STAGE GASIFIER AND INTERNAL COMBUSTION ENGINES OF VARIOUS POWER OUTPUTS

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Abstract. The paper is concerned with an integrated system of internal combustion engine and mini combined heat and power plant (ICE-CHP). The system is based on multi-stage wood biomass gasification. The use of producer gas in the system affects negatively the internal combustion engine performance and, therefore, reduces the efficiency of the ICE-CHP plant. A mathematical model of an internal combustion engine running on low-calorie producer gas was developed using an overview of Russian and foreign manufacturers of reciprocating units, that was made in the research. A thermal calculation was done for four-stroke gas engines of different rated power outputs (30, 100 and 250 kW), running on producer gas ($\text{CO}_2 - 10.2$, $\text{CO} - 45.8$, $\text{N}_2 - 38.8\%$). Thermal calculation demonstrates that the engine exhaust gas temperature reaches $500 - 600^\circ\text{C}$ at the rated power level and with the lower engine power, the temperature gets higher. For example, for an internal combustion engine power of 1000 kW the temperature of exhaust gases equals 400°C . A comparison of the efficiency of engine operation on natural gas and producer gas shows that with the use of producer gas the power output declines from 300 to 250 kW. The reduction in the effective efficiency in this case makes up 2%. The measures are proposed to upgrade the internal combustion engine to enable it to run on low-calorie producer gas.

1. Introduction

Natural gas can be used as a fuel in spark-ignition carburetor internal combustion engines for stationary and transport applications. The main type of engines running on gaseous fuel is stationary internal combustion engines that are normally used in low-power gas engine power plants. The primary fuel is natural gas.

In terms of design, gas-fuelled engine represents an ordinary spark-ignition carburetor internal combustion engine. Energy of fuel combustion in the engine cylinders performs mechanical work that provides operation of generators generating electric power.

A great advantage of gas-fuelled engine power plants is their capability to operate on different types of gas (for example, natural gas and industrial gas). Under the industrial gas we understand gas obtained in oil production and refining, sewage gas and gas produced by specially processing solid fuels (gasification). Specific calorific value of an alternative gas is much lower than that of natural gas ($33-35 \text{ MJ/m}^3$) and makes up $10-25 \text{ MJ/m}^3$.



Efficiency may be reduced due to the lower energy density of the gas-air mixture and the power loss associated with the suction efficiency of the process mixture to the engine.

The study of application of low-calorific gases for small-scale power plants is being carried out by scientists from different countries [1-3]. Many of them think that the multi-stage gasification technologies of solid fuels (coal, biomass, etc.) are used to improve the quality of synthesis gas [1, 2].

Solution to the problem of optimizing systems allows to increase the efficiency and economy of heterogeneous solid fuel plants [4-6]. Some of the researchers are engaged in the investigation work of an internal combustion engine (ICE) on gases produced during the gasification of solid fuels, particularly biomass or coal [7-9].

2. Specific features of internal combustion engine operation on low-calorie fuel

Associated or flare gas is one of the fuel subtypes of the natural gas group. Associated gas produced along with oil consists mainly of methane of heavy hydrocarbons. Predominance of these substances leads to detonation combustion and requires special adaptation of gas engines. Local use of associated gas can provide both electricity and heat supply to the fields in the most remote areas. Thus, the problem of environmentally friendly utilization can be solved rationally and cost-effectively.

The flare gas is a valuable energy feedstock that can be used more rationally with the help of special equipment. For example, in 1997 the Brazil oil company "Petrobras" installed a module manufactured by the Austrian company "Jenbacher". The energy generated by it is used to preheat crude oil. Approximately 250 m³ of flare gas per hour produces 1.164 kW of electricity and 1.708 kW of heat, instead of heating the atmosphere and causing reproach from environmental organizations.

Some problems can occur when the plants operate on gas fuel, because the low-calorie gas often requires additional injection of liquid fuel (usually it is pilot oil). Dual-fuel diesel and gas engines are of interest for the use in the energy generation sector. What attracts attention is different shapes of curves demonstrating changes in the engine efficiency (Fig. 1), depending on the fuel used (liquid or gas).

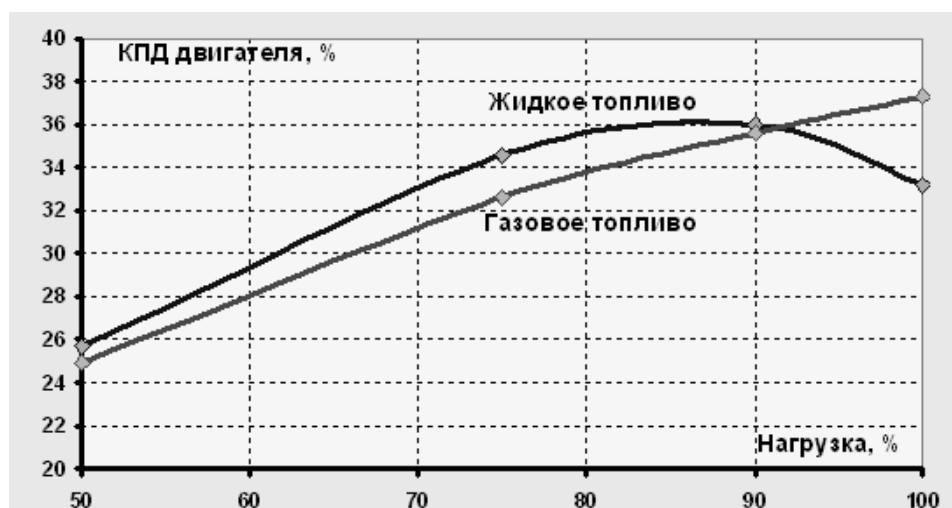


Figure 1. A relationship between the efficiency of engines running on liquid and gaseous fuel [10].

A system for alternative gas generation and a reciprocating engine power plant are normally located in the vicinity of a single system for production of syngas from organic feedstock and subsequent generation of electricity and heat.

Gas engine power generation units are developed and manufactured by many known companies in Russia and other countries [11, 12], for example, Cummins (the USA), MWM GmbH (Germany), GE Jenbacher (Austria), and MTU Onsite Energy GmbH (Germany). Some of them run not only on natural but also on alternative fuel [13] (Table 1).

Table 1. Characteristics of reciprocating engine power plants manufactured by foreign companies.

Manufacturer	Model	Electric power, kW	Thermal power, kW	Efficiency, %	Fuel utilization factor, %
Wilson with Perkins ICE	PG750	600	1035	39	88
	PG1000 B	800	904		
	PG1250 B	1000	1173		
Deutz AG	616/2016	350-1050	-	33-37	-
	620/2020				
	632/2032				
Jenbacher AB	J 208 GS	330	361	38.7-42.5	81.0-87.5
	J 212 GS	526	633		
	J 312 GS	625	746		
	J 316 GS	836	997		
	J 320 GS	1065	1197		
	J 612 GS	1644	1730		
	J 616 GS	2188	2350		
	J 620 GS	3029	3047		
Wartsila	12V34SG	3995	Determined by the project	43.4-45.1	Up to 94
	18V34SG	5993			
	20V34SG	8730			
	18V50DF	16638			
Caterpillar	DM5470	1618	813	39.9-40.9	-
	DM5467	1618	774		
	DM5469	1120	921		
	DM5466	1175	871		

There are also gas-fuelled and dual-fuel power plants manufactured by Russian companies. These include the company “Zvezda-Energetika” that manufactures 300-1800 kW energy plants that run on main gas, associated gas, biogas or liquefied gas. The JSC “Kolomensky zavod” [14] manufactures the dual-fuel plants that run on gas and diesel fuel. The main fuel is either natural gas or associated petroleum gas (85-90%), whereas diesel fuel (10-15%) is used as a pilot oil. Their power output varies in the range of 1200-1600 kW. The JSC “Penzadiselmash” manufactures 600-900 kW gas engines with liquid fuel pilot injection.

Characteristics of foreign engines running on gas fuel are superior to the Russian analogs. The offered range of power output is much wider: from 144 to 16638 kW, whereas the power output range offered by the Russian manufacturers is from 300 to 1750 kW. At the same time the values of specific gas fuel flow rates in the foreign engines are higher by 20-30%. The developments of foreign companies are more oriented to an alternative gas fuel. In Russia such a practice is not so widely used. The manufactured engines are intended for operation on natural gas or on gas and diesel.

One of the specific features of the internal combustion engines running on low-calorie fuel is a piston design adapted for operation with a higher compression ratio [15]. Galvanic coatings are used to ensure long service life of engine parts and components. High power output parameters of gas-fuelled generator plants on alternative fuel are, among other things, achieved by excluding the process of synthesis gas pre-compression.

3. Flow chart of ICE-CHP plant

During the research a design diagram of the ICE-CHP plant operating on low-calorie gas produced during biomass gasification was developed. Figure 2 presents a simplified scheme of this plant.

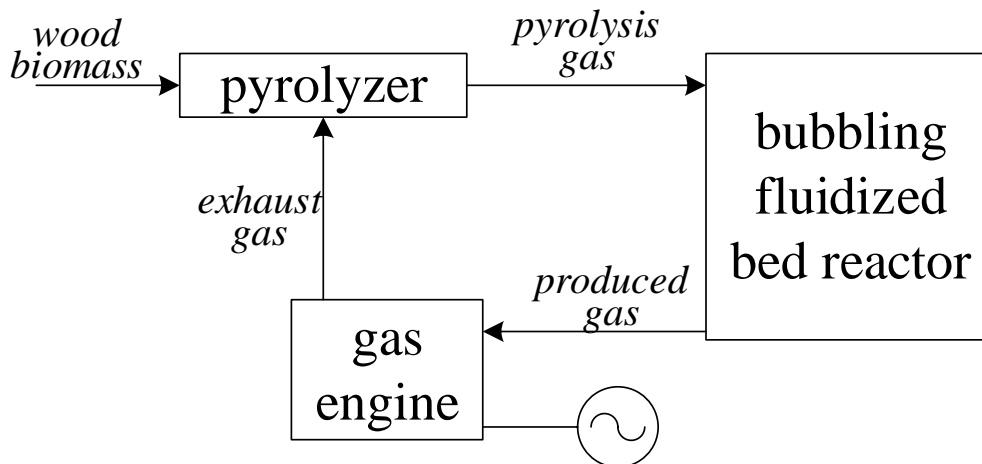


Figure 2. A schematic diagram of the producer gas plant.

According to the Figure, the initial wood biofuel goes to the first stage of the plant, i.e. pyrolyzer. In the pyrolysis zone, by heating the initial fuel with the exhaust gases of internal combustion engine, the pyrolysis gas and char are produced and are then delivered to gasification zone. In the bubbling fluidized bed reactor, the lower part of which is combined with a convector of pyrolysis gas. After the pyrolysis gases are combusted, the produced hot gases go to the char gasification area. Synthesis gas and ash are formed at the gasifier outlet. Further, to prepare the syngas for delivery to the internal combustion engine, it passes through the stages of cleaning from solid particles, cooling and removal of extra moisture. The heat produced from cooling is transferred to the air for the combustion zone, and is additionally used to heat the pyrolysis zone. The air fed to the internal combustion engine and gasifier comes from the environment. The exhaust gases after the engine are divided into two parts. The first part of these gases goes to the first stage of pyrolyzer, and the second part of the gases heated through the syngas cooling goes to the second stage of pyrolyzer. After pyrolysis, the gases can be used to heat the heating system water and then be released into the atmosphere.

4. Thermal calculation of the gas engine

Thermal calculation of a four-stroke gas-fuelled engine running on producer gas from solid fuels was made according to a method based on the data from [16-18]. The main objective of the thermal calculation is to determine the main performance parameters that characterize the efficiency and cost-effectiveness of gas engine operation.

Thermal calculation of a newly designed gas engine includes the determination of its swept volume and speed.

The initial data for the calculation are:

- Producer gas composition (CO_2 – 10.2, CO – 45.8, H_2 – 3, N_2 – 38.8%) and natural gas composition (CH_4 – 100%) in percentage.
- Producer gas flow rate and calorific value that are determined at thermal calculation of gasifier.
- Environmental conditions (pressure and ambient air temperature).

The thermal calculation of the internal combustion engine running on syngas (at an excess air factor of 1.25) was made for three variants of plant output: 30, 100 and 250 kW. The assumed gas composition was calculated based on thermodynamic equilibrium of conversion process. The efficiency of upgraded

engines and an engine running on natural gas (methane) was compared for the power of 250-300 kW (Table 2).

The calculation was made for dry gas (disregarding the external moisture). In terms of the process it is preferable to perform gas dehydration before its supply to the internal combustion engine and reduce the temperature of the gas supplied to the engine down to 40 °C. Heat from the syngas cooling can be transferred through the heat exchanger to pyrolyzer or be used to heat the air supplied to gasifier.

Table 2. Thermal calculation results for the gas-fuelled engine.

Index	Notation	Measurement unit	Syngas	Methane
Specific weight of combustible gas	γ_n	kg/nm ³	1.26	0.752
Lowest heating value of combustible gas	Q_n^c	kcal/nm ³	1474	8000
Volume of theoretically required air for combustion of a fuel volume unit	L_o	nm ³ /nm ³	1.16	8.95
Electric power of the engine	N_e	kWe	251.7	304.6
Specific effective fuel consumption	V_e	m ³ /hp hr	1.99	0.339
Specific effective heat consumption	q_e	kcal /hp hr	2940	2716
Effective engine efficiency	η_e	%	21.4	23.2
Indicator efficiency less pump losses	η_{i-c}	%	27.8	28.9

Comparison of the thermal calculation results for internal combustion engine running on syngas for three variants of the plant power (30, 100 and 250 kW) is presented in Figure 3.

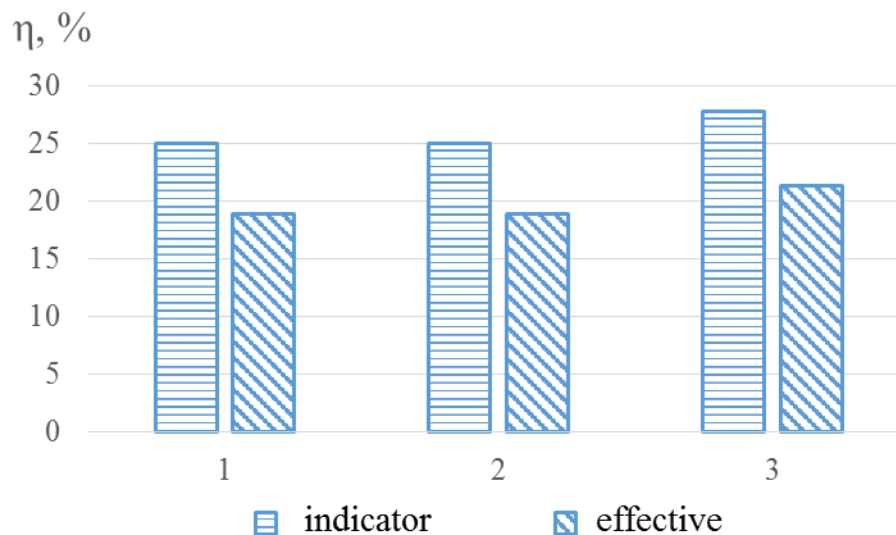


Figure 3. Effective and indicator engine efficiency versus power (kW): 1 – 30, 2 – 100, 3 – 250.

The Figure demonstrates that the indicator efficiency less pump losses rises by 2.8% at a switch to the engine power of 250 kW, but remains the same for the power of 30 and 100 kW. In this case the effective engine efficiency increases by 2.5%.

5. Conclusions

The temperature of the engine exhaust gases reaches 500-600 °C at the rated power output, and the lower the engine power, the higher the temperature. For the power of 1000 kW the temperature is about 400 °C.

The amount of heat produced per each kilowatt of power generated at gas-fuelled engine cogeneration plants makes up 1.2-1.3 kW.

When using methane as a fuel, it is necessary to assume large values of the excess air factor. In the case of syngas, the specific fuel consumption is much higher than with methane, the electric power of the engine is reduced since the engine runs on a lower calorie gas.

Gas engine provides operation of power generator, and the produced electric power is supplied to consumers. The heat released at operation of the gas engine is recovered via heat exchangers in the engine cooling system and exhaust gas system.

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